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CURRENT HEATING OF PLASMA IN A CLOSED MAGNETIC TRAP

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ABSTRACT: Experimental investigation of the effect of accelerated electrons on plasma characteristics in a closed magnetic trap. The experiments consisted of measurement of the current flow, plasma density, X-ray radiation, microwave radiation, and light emission as a function of the accelerated particle density.

Many experiments with electrical discharges and the injection of beams into a plasma, carried out on the most varied types of equipment, bear witness to the importance of the processes occurring when a group of accelerated electrons interacts with a plasma [1-3]. These so-called collective processes are to a substantial degree determined by the energy of the group of accelerated particles and the relationship of the density of these particles to that of the plasma with which they interact. /132*

High-amplitude collective oscillations may lead to substantial changes in the characteristics of the plasma: its conductivity, temperature, thermal conductivity, etc. /133

This article studies the interaction of charge particles with a plasma in a stellarator. The experiments were carried out on the Sirius closed magnetic trap, which is a racetrack with two triple helical-wound coils (Fig. 1). The basic parameters for this installation are as follows:

Axial length of vacuum chamber	$l = 600$ cm
Minimum chamber radius	$d = 10$ cm
Maximum confining field	$H_0 = 2 \cdot 10^4$ Oe
Limiting Kruskal current	$I = 5$ kA

$$\beta_c = \frac{8\pi nkT}{H_0^2} = 75 \cdot 10^{-4}.$$

It should be noted that prior to beginning the experiments with the plasma, the stellarator magnetic field was carefully adjusted, during which we studied the shape of the magnetic surfaces through repeated passage of a low-energy electron beam along the stellarator chamber.

Figure 2 shows the shape of the surfaces over the straightaway portion of the stellarator for different values of γ. The quantity γ is defined as follows: /134

$$\gamma = \frac{H_0 \epsilon}{21} \text{ ca},$$

*Numbers in the margin indicate pagination in the foreign text.

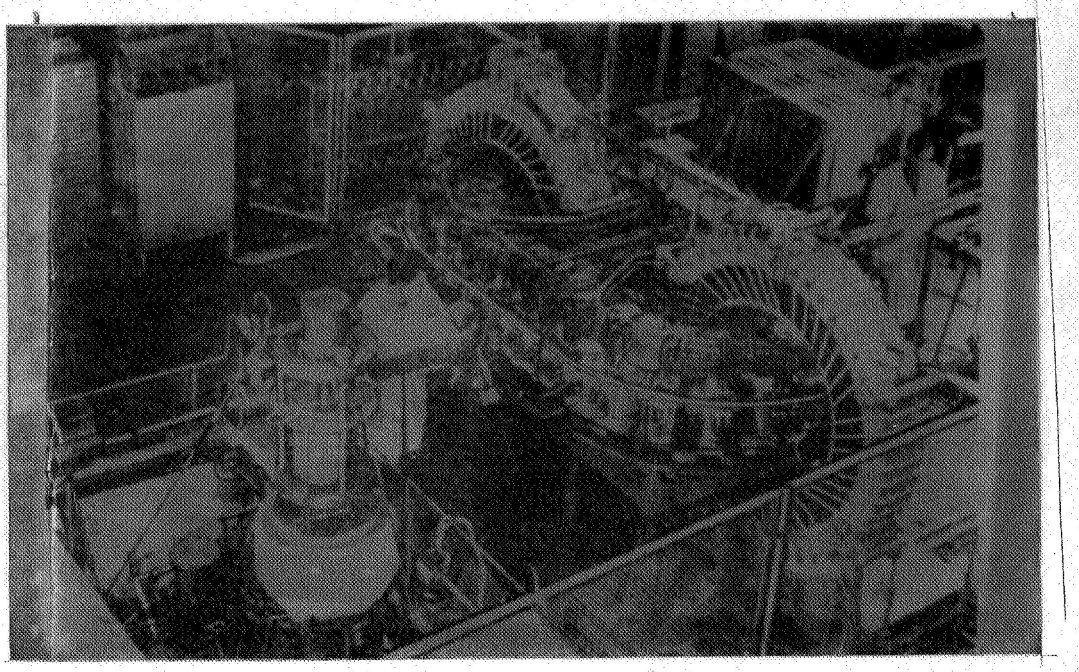

Figure 1. Overall View of Sirius Stellarator.

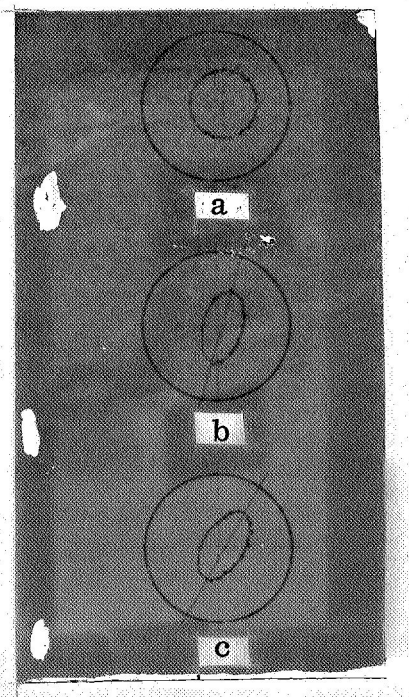

Figure 2. Shape of Magnetic Surfaces for Different Values of Parameter γ:
a — $\gamma = 4.1$; b — $\gamma = 5.09$;
c — $\gamma = 6.00$.

where $\epsilon = \frac{2\pi a}{L}$, a is the radius of the helical winding, I is the current in the helical winding, and L is the pitch of the helical winding.

For the excitation of intense collective oscillations a high-amplitude ($E \geq E_k = 1.58 \cdot 10^{-8} \frac{n}{T_e}$) longitudinal electric field is applied to the plasma created in the stellarator chamber by the pre-ionization generator [4]. This field is induced in the closed plasma column by discharging a capacitor storage bank with capacitance of 0.8 μF (charged to 5-15 kV) to the metallic portion of the stellarator vacuum chamber.

During the experiments (Fig. 3) we measured the plasma current and the chamber voltage, the plasma density, the X-ray radiation from a diaphragm limiting the dimensions of the plasma pinch and from the chamber walls, the microwave radiation from the plasma, and the integrated light. All the tests were carried out at an initial neutral helium pressure of $5 \cdot 10^{-5}$ -$8 \cdot 10^{-4}$ mm Hg.

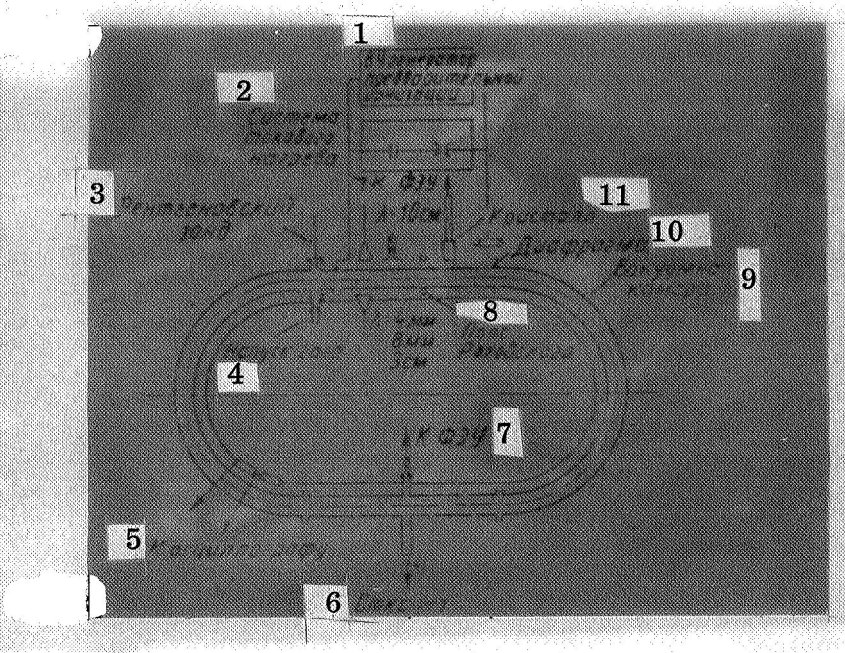

Figure 3. Diagram of "Sirius" Stellarator Instrumentation

Code: 1. high-frequency pre-ionization generator; 2. current heating system; 3. X-ray probe; 4. gas inlet; 5. to oscillograph; 6. evacuation; 7. to photomultiplier; 8. Rogowski loop; 9. vacuum chamber; 10. diaphragm; 11. crystal.

The condition $E > E_k$ is equivalent to the condition $v_0 > v_T$, where v_0 and v_T /135 are the velocity of the accelerated electrons and the thermal velocity of the plasma electrons, respectively. For initial thermal velocities close to 10 eV and plasma densities $n = 10^{13}$ cm^{-3}, the corresponding critical current densities for excitation of the collective oscillations are $j = env_T \simeq 180 - 250$ A / cm^2.

Experiments have shown that oscillations develop when the total current is 2 to 3 kA, which corresponds to current densities $j = 100 - 150$ A/cm^2.

Figures 4 and 5 show two series of oscillograms obtained for two different ratios of applied electric field and critical field. The value for the confining magnetic field under these conditions is 8 k0e. If the applied electric field is /136 smaller than the critical fields, the current signal has a sinusoidal shape (Fig. 4a). As the electric field is increased, the current signal becomes distorted and, for $E > E_k$, after reaching I = 2 kA, the current drops sharply to I = 100 -200 A and is maintained at that level for 10 - 20 μ sec although a large electric field is applied to the plasma at this time (Fig. 5a).

Figure 6 shows the discharge current as a function of the initial neutral gas pressure with the voltage of the capacitor bank as parameter. To a certain degree, this is equivalent to the dependence of the current on the ratio of the applied field to the critical field. A decrease in the current at each of the derived curves is observed for an electric field of $E \approx E_k$.

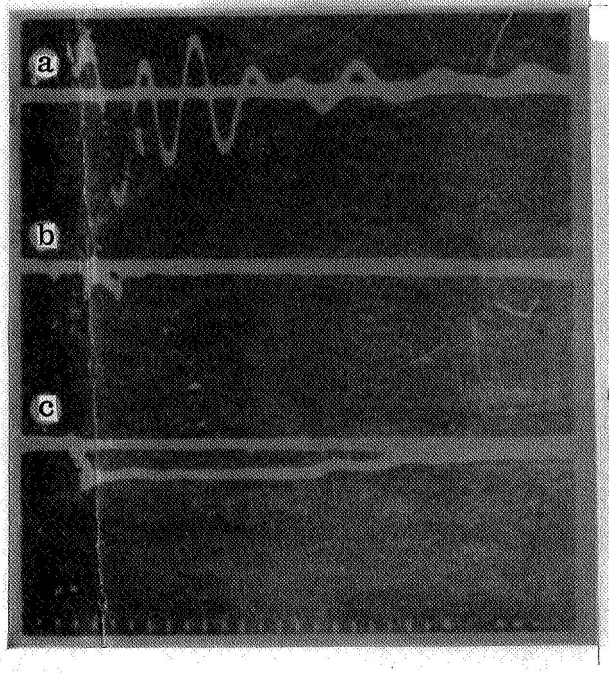

Figure 4. Oscillograms of Current (a), of Microwave radiation at Wavelength $\lambda = 3$ cm (b), and of Integrated Discharge Light (c) with Electric Field Intensity $E < E_k$.

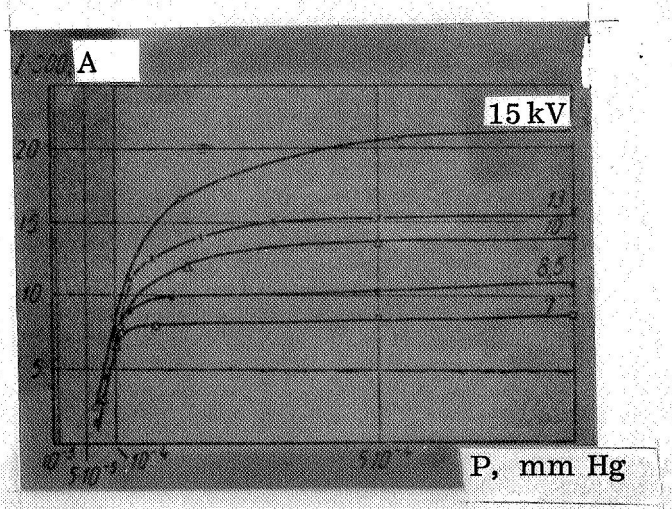

Figure 6. Dependence of Discharge Current on Pressure with Voltage of Capacitor Bank as Parameter.

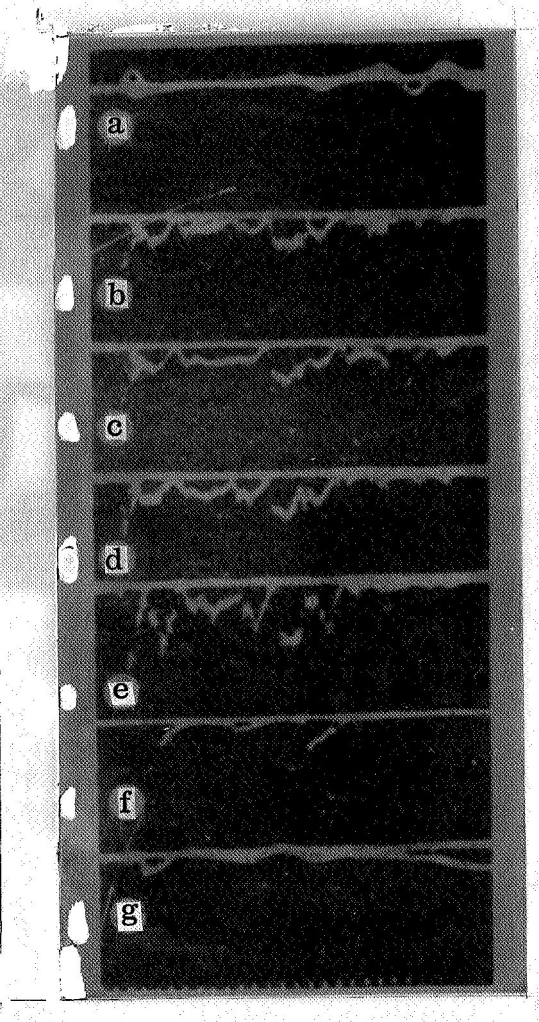

Figure 5. Oscillograms of Current (a), of Microwave Radiation at Wavelengths $\lambda = 7.5 - 600$ cm (b - e) of X-ray Radiation (f) and of Integrated Discharge Light (g) with Electric Field Intensity $E > E_k$.

Investigation of the plasma impedance Z as a function of the applied field has shown that it changes little at field strengths below critical and increases with an increase in the field above critical. With a change in the electric field from $E = 2E_k$ to $E = 10E_k$ the plasma impedance increases from 1 to 8 ohms (Fig. 7).

In all intervals of the investigated neutral helium pressures and electric and magnetic field strengths, the discharge was accompanied by microwave radiation from the plasma. With the electric field strength below critical, the microwave radiation is more intense in the wavelength region $\lambda = 2 - 4$ cm, i.e., in the /137

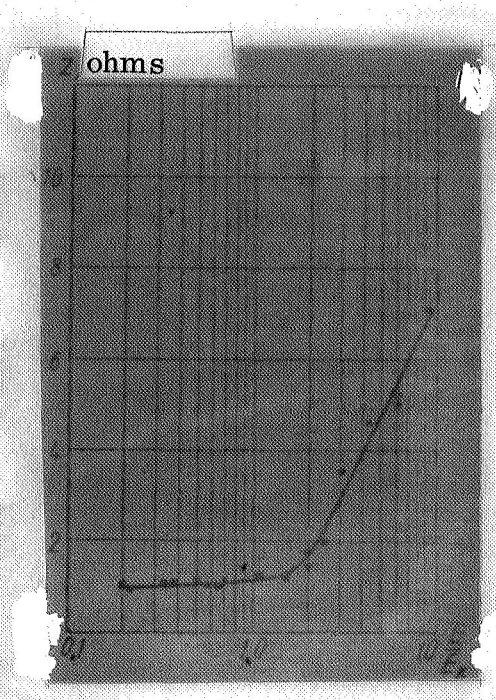

Figure 7. Plasma Impedance Z as a Function of Electric Field Strength.

immediate vicinity of the Langmuir frequency.

It should be noted, however, that no radiation was observed directly at the Langmuir frequency, although high-sensitivity instruments were used in searching for it. With an increase in the electric field, the power radiated in the wavelength region of $\lambda = 2 - 4$ cm increases and reaches a maximum at $\frac{E}{E_k} = 2 - 4$. A further increase of $\frac{E}{E_k}$ leads to attenuation of the radiation in this wavelength region. In addition, at an electric field strength of $E < E_k$ a broad spectrum of oscillations is excited in the plasma in the wavelength range of $\lambda = 4.6 - 600$ cm (Fig. 5, b-e), the maximum of the radiated power occurring in the interval $\lambda = 12 - 15$ cm. In our case, this corresponds to the Buneman frequency $\omega = \omega_0 \sqrt{\frac{m}{M}}$, where ω_0 is the Langmuir frequency and M is the ion mass. Within the intervals of $\lambda = 2.6 - 3.6$ cm and $\lambda = 7.5 - 10$ cm Fig. 8 shows the radiated power as a function of plasma density with constant voltage at the capacitor bank. Evaluation of the peak radiated power in the wavelength region of $\lambda = 2.6 - 3.6$ cm yields a value on the order of 100 W, while for $\lambda = 7.5 - 10$ cm it is approximately 1000 W from the entire surface of the plasma pinch.

At above-critical electric fields the plasma is a source of intense X-ray radiation (Fig. 5, f). This radiation is recorded at the moment instability arises from the diaphragm limiting the dimensions of the plasma pinch as well as from the chamber walls and the X-ray probe located in the chamber at the boundary of the plasma. Study of the absorption spectra of the X-ray radiation from the diaphragm and from the chamber walls has shown that there are two different groups of electrons in the discharge. If at the diaphragm there is discharged a beam with energy $W = 100 - 200$ keV, which corresponds to an electron acceleration $W = (eEt)^2 / 2m = 9 \cdot 10^4$ eV in a field $E \simeq 10$ V/cm during time $t = 1$ μsec, then from the absorption spectra of the x-ray radiation from the chamber walls we may conclude that there is a group of electrons in the plasma which have a near-Maxwellian velocity distribution and whose temperature varies within the limits 4 - 9 keV upon charging the current-heating battery up to 10 - 15 kV. It is interesting to note that the temperature, calculated from the plasma conductivity in the presence of instabilities is on the order of tenths of an electron volt.

Measurement of the integrated light has shown (Fig. 5, g) that the intensity of the plasma decreases sharply at the moment of excitation of the collective process and the appearance of X-ray radiation from the chamber walls. This indirectly supports the existence of an electron heating process. /138

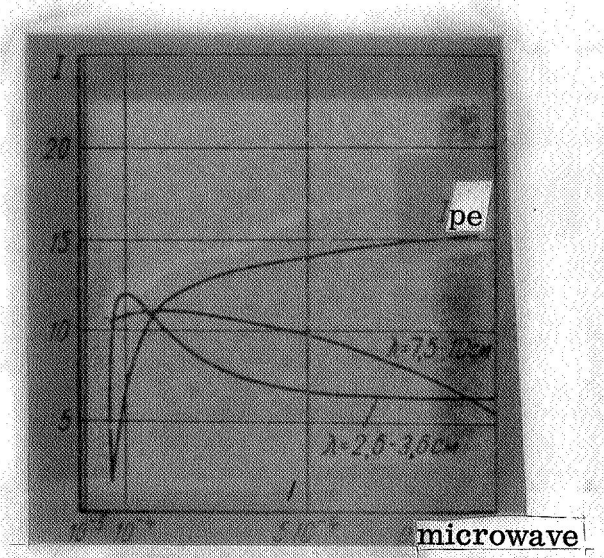

Figure 8. Intensity of Microwave Radiation from the Plasma as a Function of Pressure.

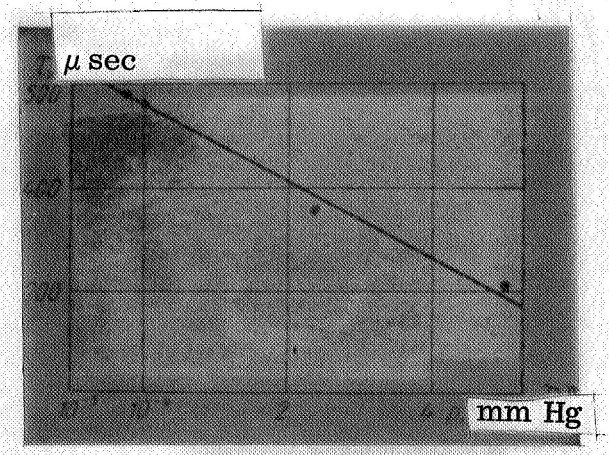

Figure 9. Plasma Confinement Time as a Function of Pressure (H = 8 Oe).

The magnetic field intensities at which the experiments were conducted (6 - 12 kOe) do not permit our hoping for a particularly long plasma confinement in the trap because the gas-kinetic pressure of the plasma is substantially greater than that at which the stellarator may operate as a trap. Obviously this results first of all in a rapid cooling of the plasma.

Investigations have shown that the confinement time for the cooled plasma increases with a decrease in the particle density (Fig. 9). The character of this dependence attests primarily to the necessity of decreasing the plasma density in in the stellarator chamber with the object of fulfilling the condition $nkT < \beta\frac{H^2}{8\pi}$.

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